



On the fraction of star formation occurring in bound stellar clusters

(JMDK12, submitted)



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Why care about bound vs. unbound cluster formation?

- ✧ Affects efficiency of galactic scale feedback

Strickland & Stevens 99, Hopkins+12, Krause+12

- ✧ Important when tracing galaxy evolution (e.g. SFH) using clusters

Larsen+01, Bastian+05, Smith+07

- ✧ Crucial in understanding cluster formation and evolution

Lada & Lada 03, Gieles+05, Elmegreen 08



QUESTION

How do star clusters form?

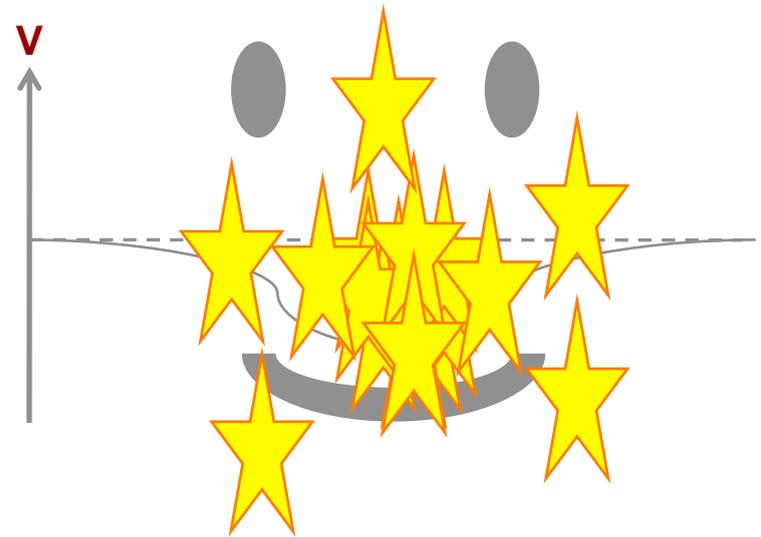
Or: what fraction of all stars is born in bound stellar clusters?

Star cluster formation: classical picture

- ✧ Classical picture: bound cluster formation inhibited by gas expulsion
Hills 80, Lada+84, Geyer & Burkert 01, Lada & Lada 03, Boily & Kroupa 03, Goodwin & Bastian 06, Baumgardt & Kroupa 07, Parmentier+08, ...

- ✧ All stars form in clusters
- ✧ Gas & stars in virial equilibrium
- ✧ Feedback expels remaining gas

- ✧ Because SFE is low: cluster *expands*, possibly becoming unbound
- ✧ Only ~10% of all star formation ends up in bound clusters





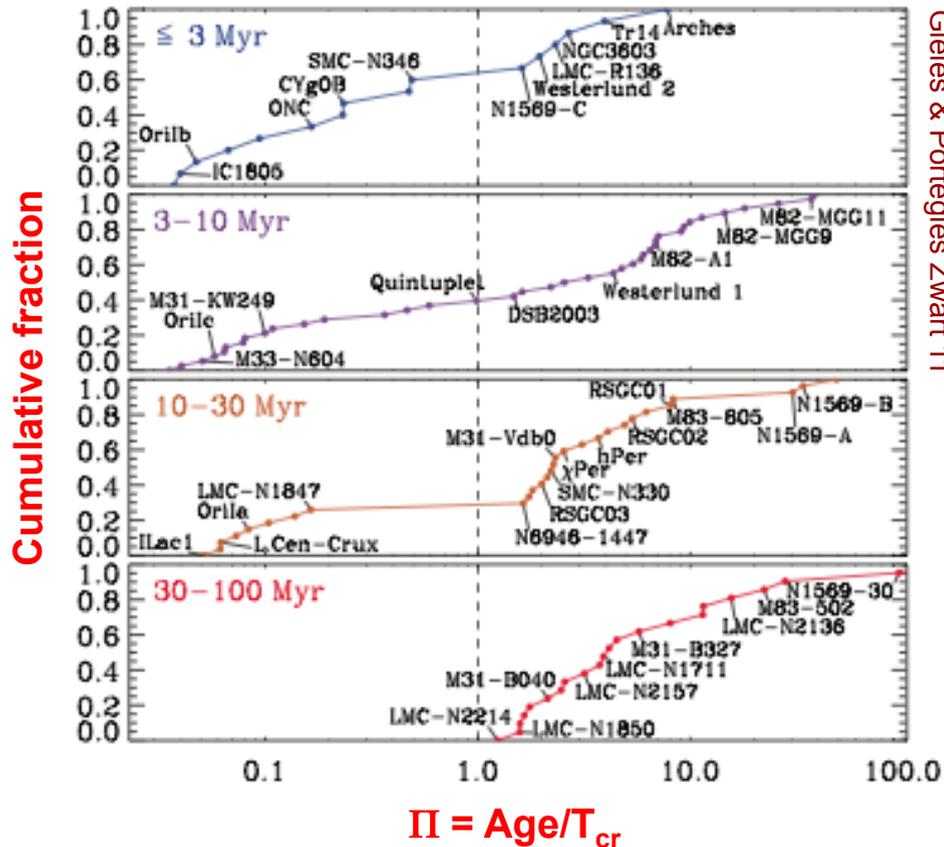
Little observational evidence for gas expulsion as key mechanism

- ✧ NGC 3603 is ~virialised and not expanding Rochau+10
- ✧ Westerlund I is ~virialised and not expanding Cottaar+12
- ✧ R136 is ~virialised and not expanding Hénault-Brunet+12
- ✧ Arches Cluster is ~virialised and not expanding Clarkson+12

Star cluster formation

✧ Not all stars form in clusters

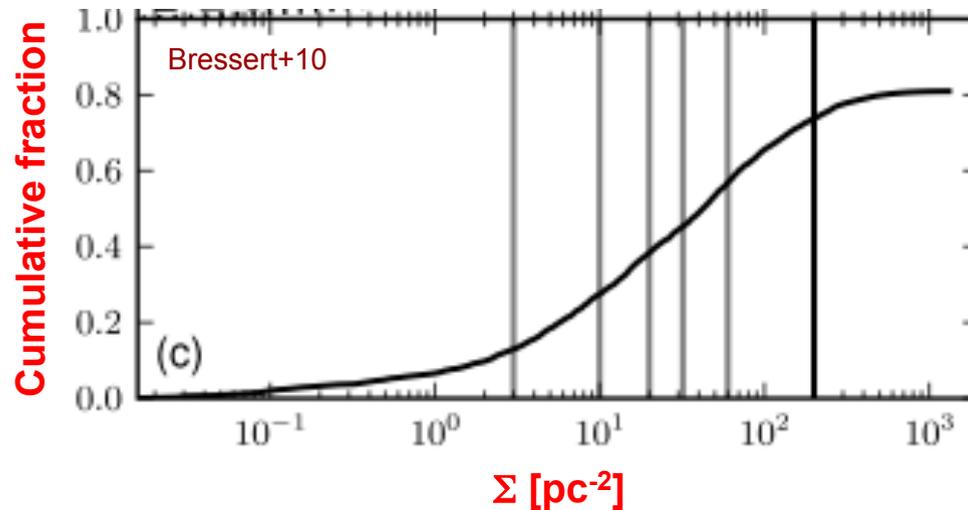
Bastian 08, Gieles & Portegies Zwart 11



Gieles & Portegies Zwart 11

Star cluster formation

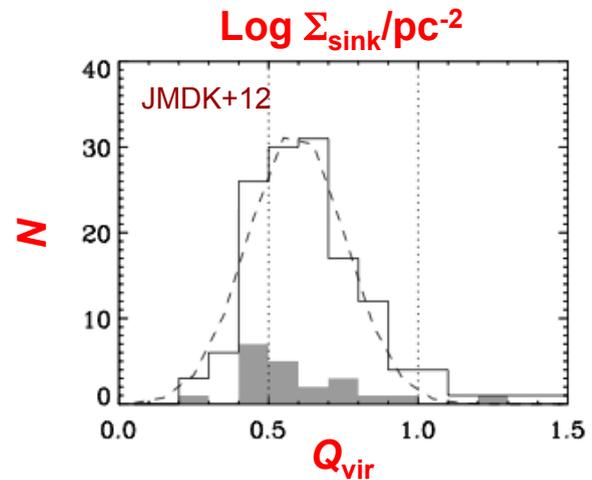
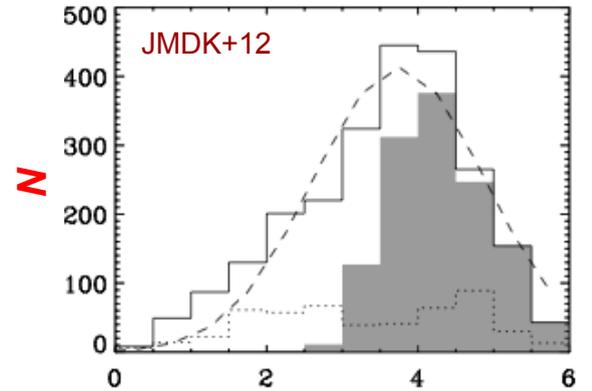
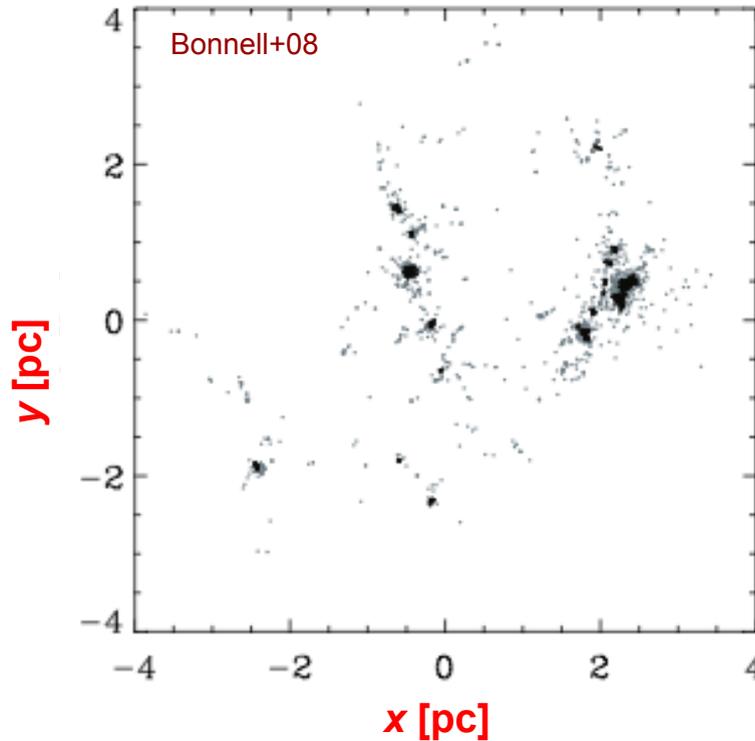
- ✧ Continuous density spectrum of star formation
Bressert+10



Star cluster formation

✧ Gas-poor & bound structure arises at the high-density end of the spectrum

Elmegreen 08, JMDK+12, Girichidis+12





Star cluster formation

- ✧ No “infant mortality” by gas expulsion
- ✧ Star clusters are not a “fundamental unit of star formation”
- ✧ Star formation process is (initially) globally scale-free





Introduction

Model

Applications

Conclusions

So... what *does* happen?



Introduction

Model

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Can we derive a theoretical framework for the *cluster formation efficiency*?

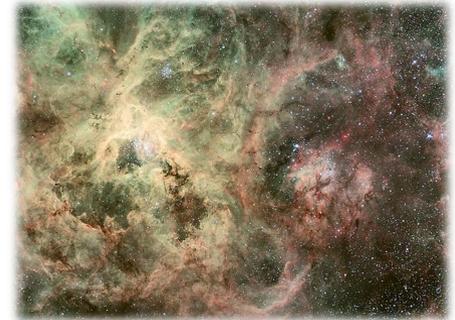
A “Dutch cheese” model





Two important mechanisms

- ✧ The naturally bound/unbound part of star formation
- ✧ The cruel cradle effect



$$\Gamma = f_{\text{bound}} f_{\text{cce}}$$

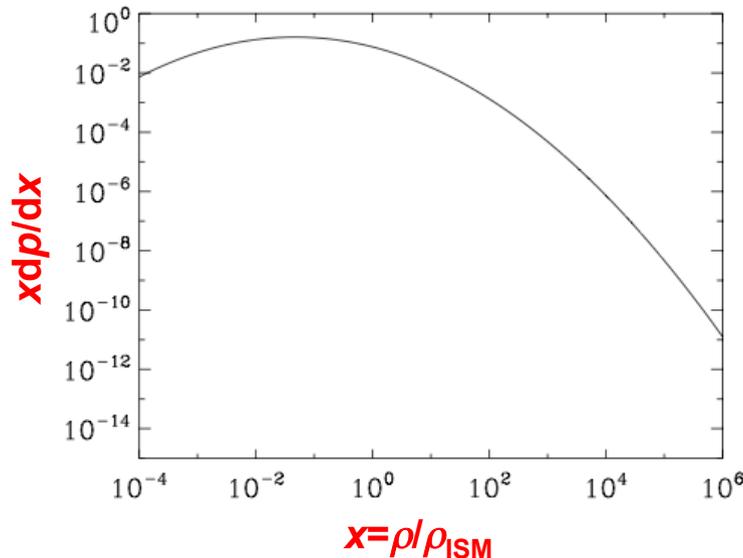
The model in one figure

- ✧ Overdensity PDF of the interstellar medium

Vazquez-Semadini 94, Padoan & Nordlund 97,11

- Surface density
- Angular velocity
- Toomre Q parameter

- ✧ Mean and dispersion set by Mach number $\mathcal{M}(\Sigma_g, \Omega, Q)$



- ✧ Assuming hydrostatic equilibrium provides mid-plane density $\rho_{\text{ISM}}(\Omega, Q)$

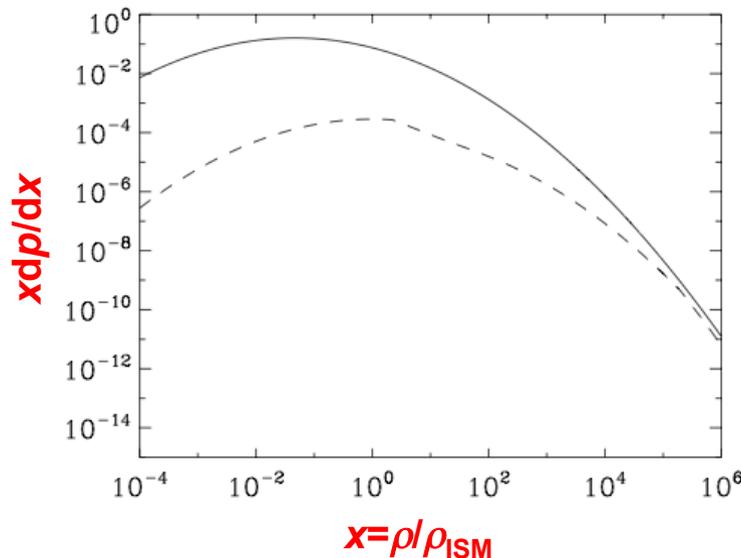
The model in one figure

- ✧ Assume specific SFR per free-fall time

Elmegreen 02, Krumholz & McKee 05

- Surface density
- Angular velocity
- Toomre Q parameter

- ✧ Pressure equilibrium between feedback and ISM gives duration of SF

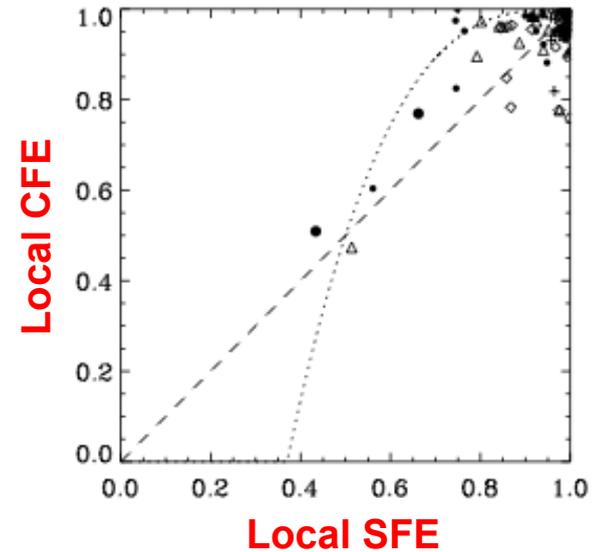
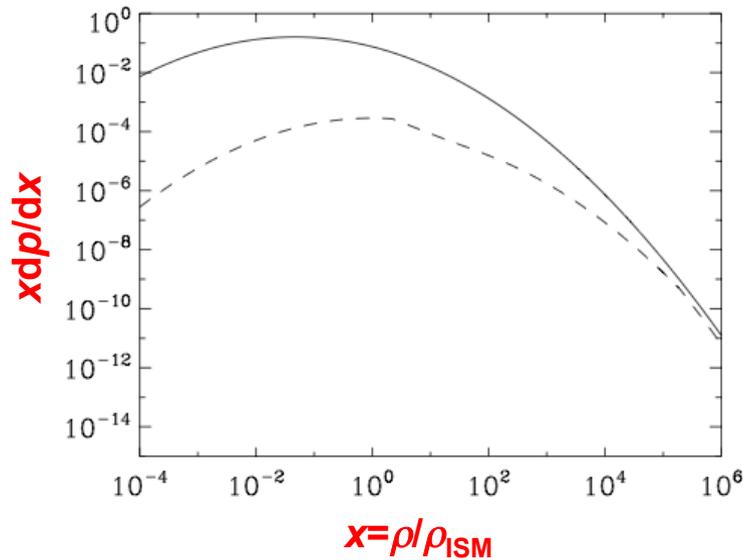


- Including the star formation efficiency

- ✧ Integration of dashed curve: all star formation

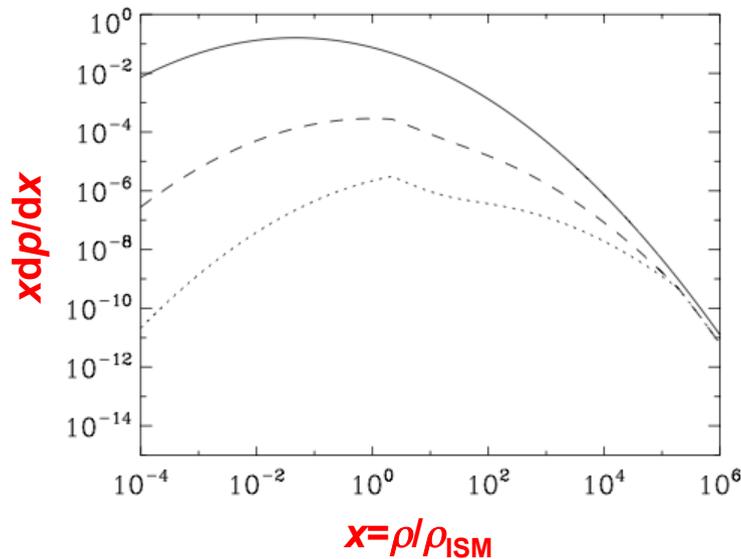
The model in one figure

- Surface density
- Angular velocity
- Toomre Q parameter



The model in one figure

- Surface density
- Angular velocity
- Toomre Q parameter



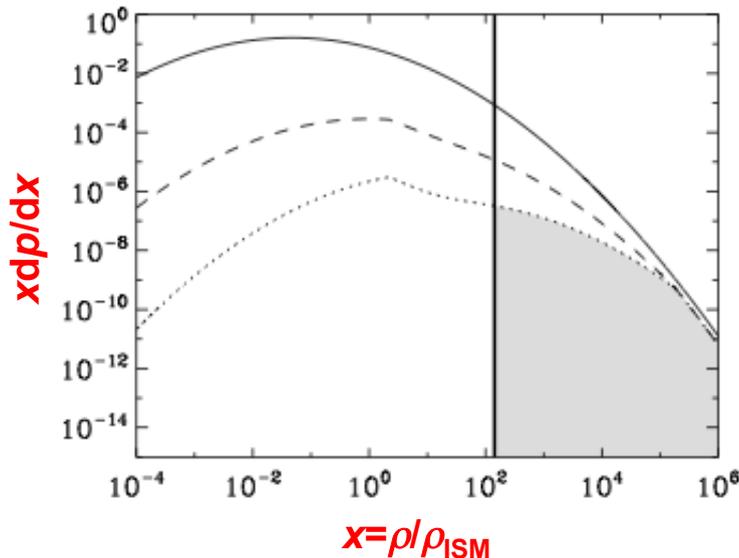
- Including the star formation efficiency
- Including naturally bound star formation

✧ Integration of dotted curve: naturally bound part of star formation

The model in one figure

- ✧ Cruel cradle effect: Spitzer theory of tidal shocks
- ✧ Critical overdensity for surviving tidal disruption by SF environment

- Surface density
- Angular velocity
- Toomre Q parameter



- Including the star formation efficiency
- Including naturally bound star formation
- Including the cruel cradle effect

- ✧ Integration gives the total cluster formation efficiency



We now have the *global* CFE as a function of:

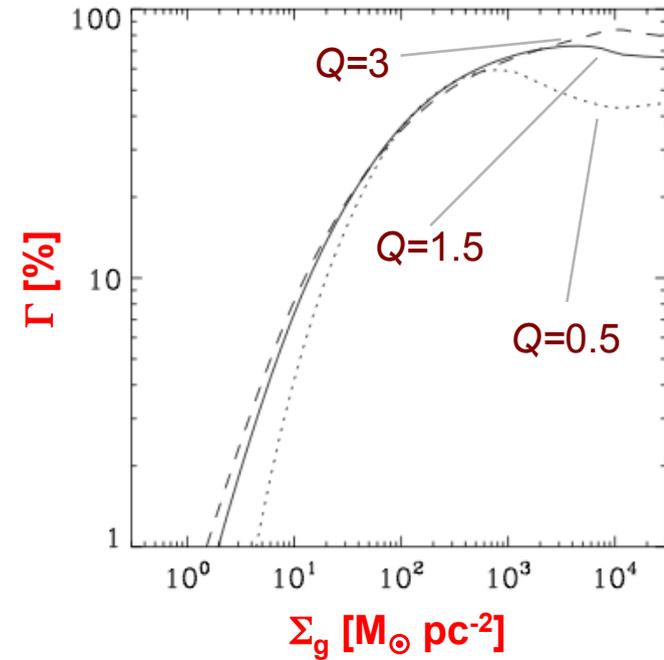
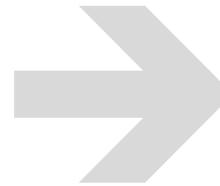
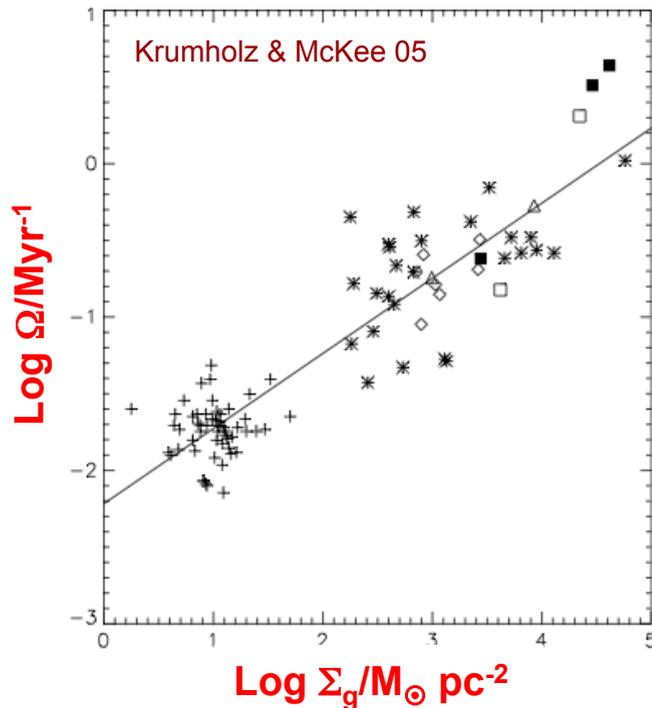
- gas surface density
- angular velocity
- Toomre Q parameter

or *locally* as a function of:

- gas volume density
- gas velocity dispersion
- sound speed

CFE as a function of... galaxy

- ✧ Need surface density, angular velocity and Toomre Q
- ✧ $Q = \{0.5, 1.5, 3\}$ for {starburst, disc, quiescent}

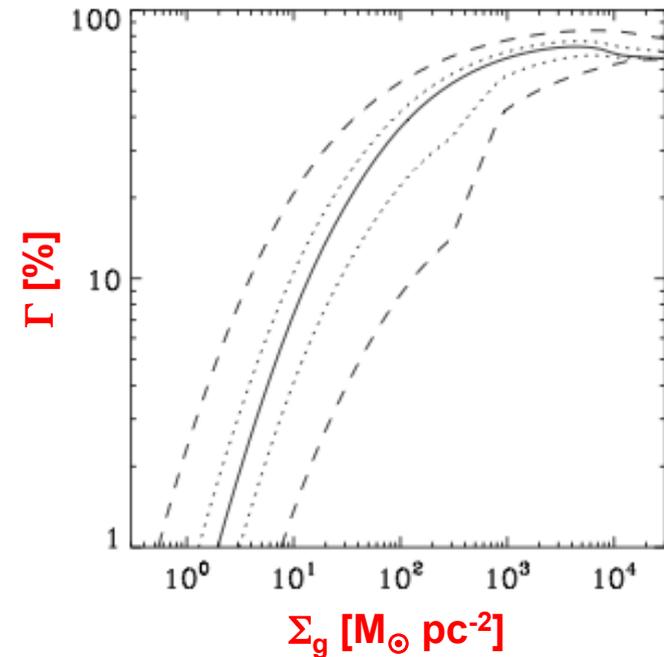


Dutch cheese revisited: model uncertainties

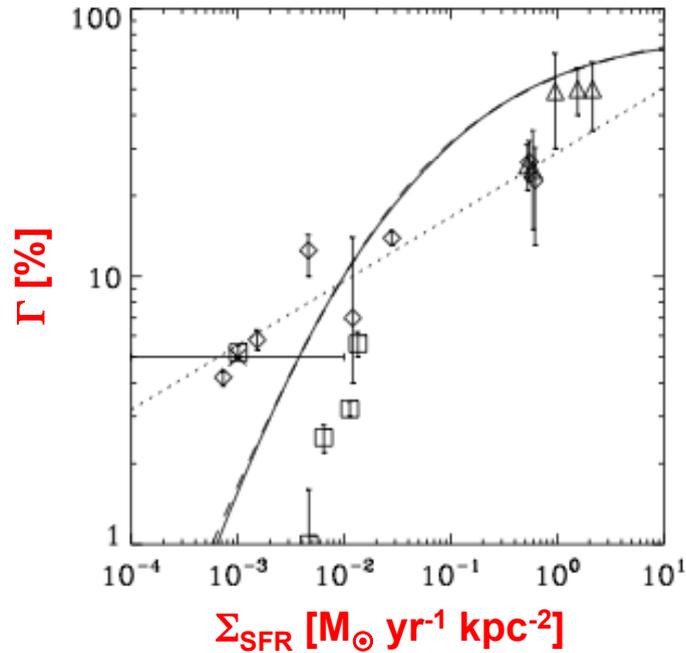
✧ Do the holes matter?



Parameter (1)	Minimum (2)	Maximum (3)	Impact on CFE (4)
ϕ_P	1	6	+
α_{vir}	1	2	+
t_{sn}	2 Myr	5 Myr	+
t	5 Myr	20 Myr	-
ϕ_{fb}	$0.032 \text{ cm}^2 \text{ s}^{-3}$	$0.8 \text{ cm}^2 \text{ s}^{-3}$	+
ϵ_{core}	0.25	0.75	-
f	0.5	0.9	-
g	1	2	-
ϕ_{sh}	2	3	-
$\Sigma_{\text{GMC}}^{\text{LG}}$	$30 \text{ M}_{\odot} \text{ pc}^{-2}$	$300 \text{ M}_{\odot} \text{ pc}^{-2}$	-



Comparison to nearby dwarf, spiral and starburst galaxies

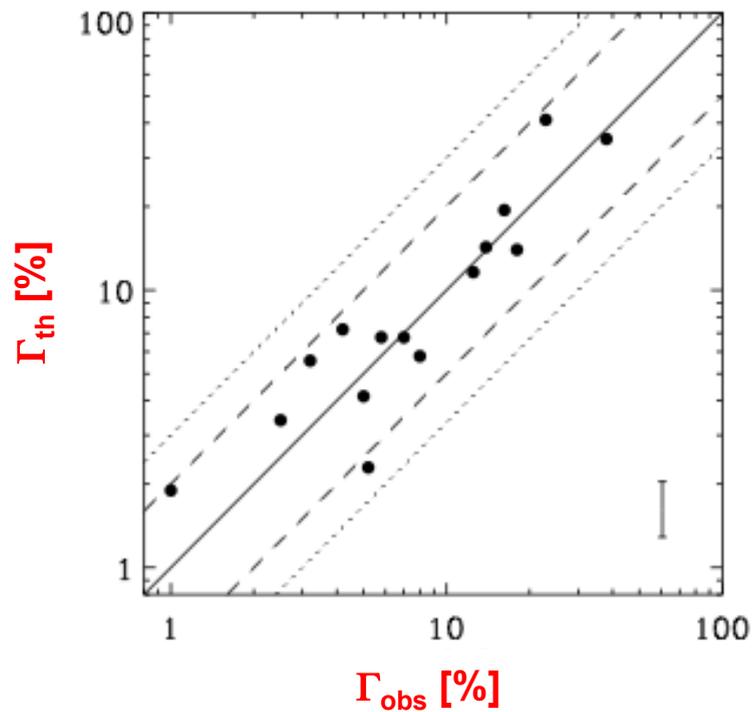


Observations

- Goddard+10
- Silva-Villa+11
- Adamo+11
- Cook+12



Comparison to nearby dwarf, spiral and starburst galaxies





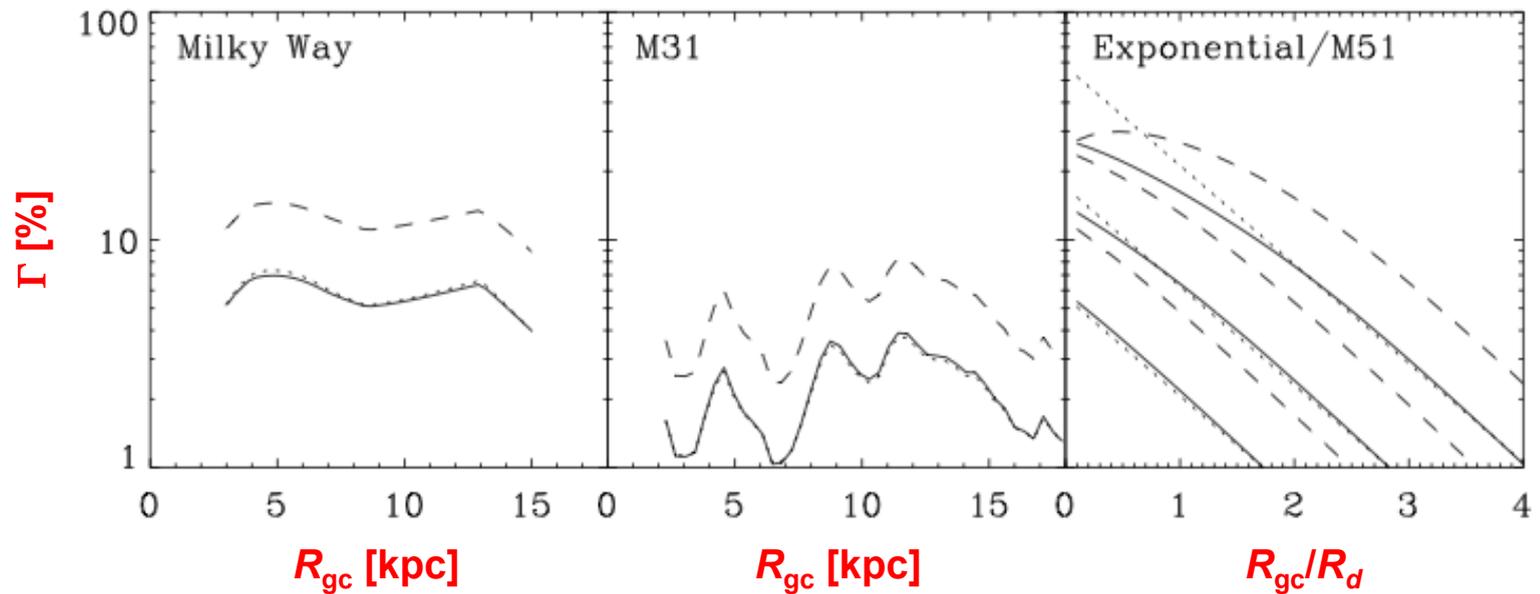
Introduction

Model

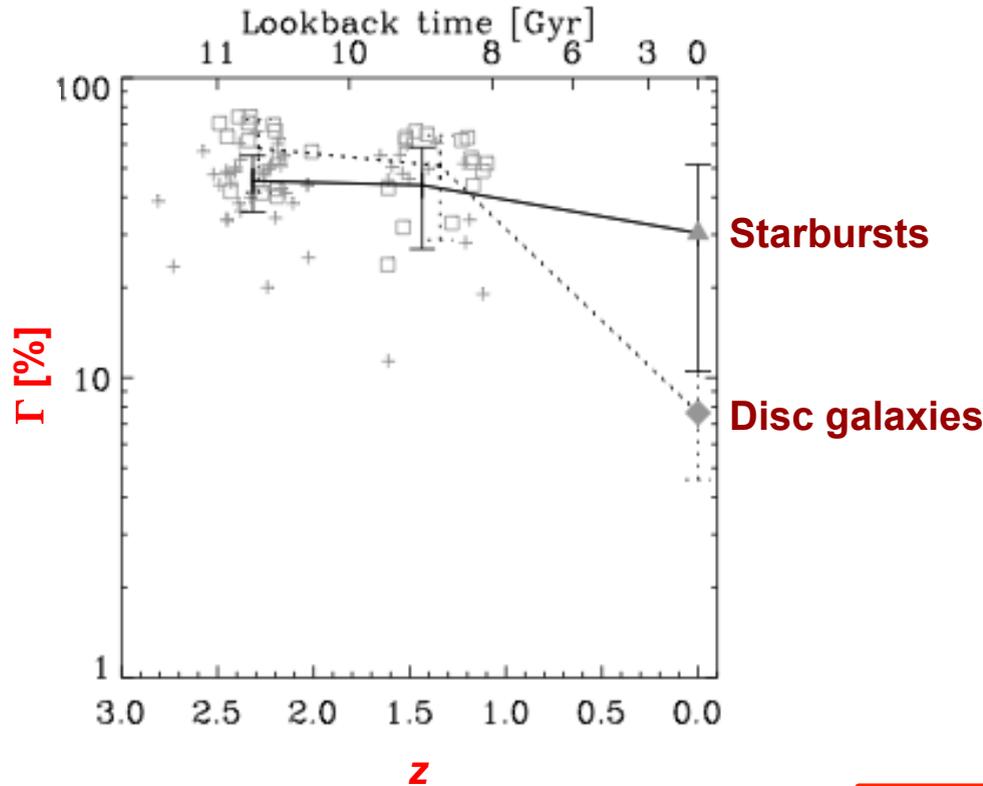
Applications

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Spatially resolved cluster formation efficiency



Cosmic evolution of the cluster formation efficiency



Input from Observations

- Kennicutt 98
- Tacconi+08
- Förster Schreiber+09
- Tacconi+10
- Genzel+10

$$\Gamma_{\text{univ}} = 30-35\%$$



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QUESTION

How do star clusters form?



MODEL ANSWER

Star clusters form at the high-density tail of the ISM density spectrum

&

We can now predict the fraction of star formation that is clustered versus the fraction that is dispersed



OBSERVATIONS

***Gaia* can verify whether gas expulsion acts on substructured (should) or collapsed, spherically symmetric (shouldn't) stellar structure**

&

Galactic ISM surveys should look for protoclusters and compare to the unembedded young cluster population



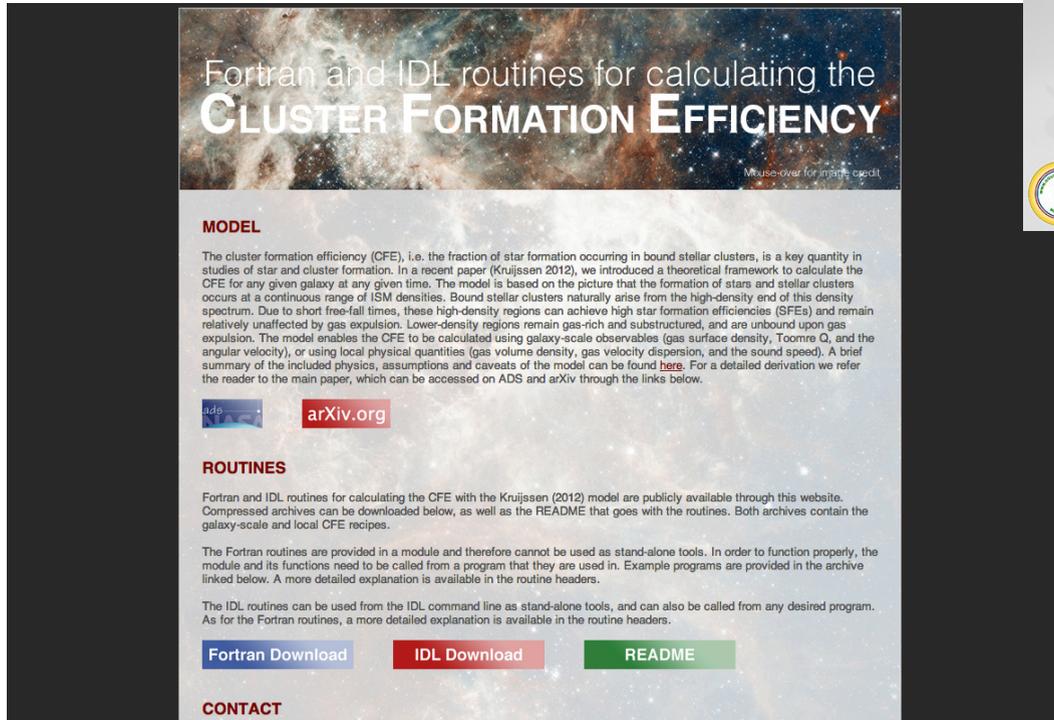
IMPLICATIONS

**The information for the star cluster formation process
is already present in the characteristics of the gas**

&

**Star clusters are no fundamental unit of star formation,
but instead are a possible outcome**

Feeling cheesy?



Fortran and IDL routines for calculating the
CLUSTER FORMATION EFFICIENCY

MODEL

The cluster formation efficiency (CFE), i.e. the fraction of star formation occurring in bound stellar clusters, is a key quantity in studies of star and cluster formation. In a recent paper (Kruijssen 2012), we introduced a theoretical framework to calculate the CFE for any given galaxy at any given time. The model is based on the picture that the formation of stars and stellar clusters occurs at a continuous range of ISM densities. Bound stellar clusters naturally arise from the high-density end of this density spectrum. Due to short free-fall times, these high-density regions can achieve high star formation efficiencies (SFEs) and remain relatively unaffected by gas expulsion. Lower-density regions remain gas-rich and substructured, and are unbound upon gas expulsion. The model enables the CFE to be calculated using galaxy-scale observables (gas surface density, Toomre Q, and the angular velocity), or using local physical quantities (gas volume density, gas velocity dispersion, and the sound speed). A brief summary of the included physics, assumptions and caveats of the model can be found [here](#). For a detailed derivation we refer the reader to the main paper, which can be accessed on ADS and arXiv through the links below.

[ads](#) [arXiv.org](#)

ROUTINES

Fortran and IDL routines for calculating the CFE with the Kruijssen (2012) model are publicly available through this website. Compressed archives can be downloaded below, as well as the README that goes with the routines. Both archives contain the galaxy-scale and local CFE recipes.

The Fortran routines are provided in a module and therefore cannot be used as stand-alone tools. In order to function properly, the module and its functions need to be called from a program that they are used in. Example programs are provided in the archive linked below. A more detailed explanation is available in the routine headers.

The IDL routines can be used from the IDL command line as stand-alone tools, and can also be called from any desired program. As for the Fortran routines, a more detailed explanation is available in the routine headers.

[Fortran Download](#) [IDL Download](#) [README](#)

CONTACT

Publicly available Fortran and IDL routines upon paper acceptance

<http://www.mpa-garching.mpg.de/cfe>

(don't try, there's nothing there yet)